



CIRRELT

Centre interuniversitaire de recherche
sur les réseaux d'entreprise, la logistique et le transport

Interuniversity Research Centre
on Enterprise Networks, Logistics and Transportation

Three-Echelon Supply Chain Management for Disaster Relief Operations

Snezana Mitrovic Minic
Michel Gendreau
Jean-Yves Potvin
Jean Berger
John Conrad
Darren Thomson

June 2014

CIRRELT-2014-28

Bureaux de Montréal :
Université de Montréal
Pavillon André-Aisenstadt
C.P. 6128, succursale Centre-ville
Montréal (Québec)
Canada H3C 3J7
Téléphone : 514 343-7575
Télécopie : 514 343-7121

Bureaux de Québec :
Université Laval
Pavillon Palasis-Prince
2325, de la Terrasse, bureau 2642
Québec (Québec)
Canada G1V 0A6
Téléphone : 418 656-2073
Télécopie : 418 656-2624

www.cirrelt.ca

Three-Echelon Supply Chain Management for Disaster Relief Operations

Snezana Mitrovic Minic^{1,*}, Michel Gendreau^{2,3}, Jean-Yves Potvin^{2,4}, Jean Berger⁵,
John Conrad⁶, Darren Thomson¹

¹ MDA, 13800 Commerce Parkway, Richmond, British Columbia, Canada V6V 2J3

² Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT)

³ Department of Mathematics and Industrial Engineering, Polytechnique Montréal, P.O. Box 6079, Station Centre-ville, Montréal, Canada H3C 3A7

⁴ Department of Computer Science and Operations Research, Université de Montréal, P.O. Box 6128, Station Centre-Ville, Montréal, Canada H3C 3J7

⁵ Defence Research and Development, 2459 de la Bravoure Road, Valcartier, QC, Canada G3J 1X5

⁶ Proprietor Consultant

Abstract. Humanitarian missions are complex operations that require significant resources, including equipment, medical supplies, and food. For these operations to be effective, it is important to ensure that resources are provided and supported in a cost effective and timely fashion. This report describes the design and development of models and algorithms to improve distribution and inventory management of resources for such missions. The scope addressed is a three-echelon Supply Chain Network (SCN). Challenges addressed and novelties of the models include: (a) integration of inventory management and distribution management, (b) simultaneously addressing several realistic features of supply chain management within one problem, (c) having an extended network that includes the different scales for transportation times, and (d) the intrinsic complexities of multi-echelon, multiperiod discrete optimization problems. Both deterministic and stochastic problems are addressed. The work done is an advancement on providing tools for disaster relief logistics leaders to optimise supply chain management and use of resources and hence reduce time and costs in delivering supplies such as food, water, medicine and equipment.

Keywords: Supply chain management, multi-echelon, integrated distribution and inventory management, disaster relief operations, mixed-integer programming.

Acknowledgements. This research was funded by Defence R&D Canada – Valcartier.

Results and views expressed in this publication are the sole responsibility of the authors and do not necessarily reflect those of CIRRELT.

Les résultats et opinions contenus dans cette publication ne reflètent pas nécessairement la position du CIRRELT et n'engagent pas sa responsabilité.

* Corresponding author: smitrovicminic@mdacorporation.com

1 Introduction

This document reports on a collaborative research project involving CIRRELT, MDA Systems Ltd, DRDC-Valcartier and an independent consultant. The focus of the project was on preliminary models and algorithms for decision support in three-echelon supply chain management for disaster relief operations.

The layout of this report is as follows:

- Section 2 provides the background and the motivation for this project.
- Section 3 introduces the three-echelon supply chain management, defines our problem and its characteristics.
- Section 4 provides a literature review.
- Section 5 introduces our model for the deterministic problem and a few versions of the stochastic explicit form models.
- Section 6 presents the preliminary computational study.
- Section 7 provides conclusions.

2 Motivation and Background

This project deals with the supply chain management arising in disaster relief operations. The main focus is on the combined inventory management and distribution (transportation) management problems. The problem is based on a centralized distribution strategy. The demand is assumed to be stochastic. Motivation for this project is a result of the recommendations arising from an earlier study [MC_2011].

This project considers the supply chain network (SCN) consisting of the main far supply node, the main close supply node, the set of satellite nodes and the set of customer nodes as seen in Figure 3-1. We refer to such a SCN as the extended two-echelon SCN or the three-echelon SCN. The motivation comes from: (a) the different origin locations of the supplies, (b) the complexity of the problem, and (c) the differences between the Supply Chain Management (SCM) issues before the main far supply node (F) and beyond the main close supply node (L).

As such, the solution approaches would address the following two situations: when supplies are originating far from the disaster area, and when supplies are originating at the disaster area. In disaster relief operations, these situations may happen when dealing with international relief operations abroad, or when dealing with potential mega-disasters within Canada. For example, in the case of a mega-earthquake that may happen in Western Canada, all of Canada may be involved in the relief operation, and the origins of some supplies may be far away. Thus, the portions of the SCN that need to be considered might be as follows:

- The tactical SCN without the far supply node is sufficient to consider for the locally purchased supplies:
 - Food (80% local or from close-by locations)
 - Water (90% local or from close-by locations)
- The entire SCN has to be considered for the supplies coming from Canada-at-large or from a far-away supply location:
 - Medical supplies (90% from further locations in Canada)
 - Equipment (80% from further locations in Canada)

3 Three-Echelon Supply Chain Management Problem

This section introduces the elements of the three-echelon supply chain management problem relevant to our research by providing the structure of the supply chain network, the real-world problem characteristics, and our assumptions.

We consider an integrated inventory management and distribution management problem arising in the supply management for humanitarian operations.

3.1 Supply Chain Network Structure

The structure of the Three-Echelon SCN for disaster relief operations that we will consider is shown in Figure 3-1, and it would be able to handle:

- Disaster relief abroad
- Domestic mega-disaster: for the supplies coming from far-away locations in Canada.

Going from left to right, we have the following nodes at each level of the Three-Echelon SCN: a far supply node (F), a close supply node (L), satellite nodes (s_i), and customer nodes (c_{ij}). The left-most echelon between nodes F and L is labeled Echelon 0, the middle echelon between node L and the satellites is Echelon 1, and the right-most echelon between the satellites and the customers is Echelon 2. The terms “consumers” and “customers” and “demand nodes” are used interchangeably throughout the document to represent the nodes in the right-most level of the supply chain network.

The two-echelon SCN, without the Far Supply Node, would be sufficient to consider when dealing with relief operations for domestic disasters that can be dealt with within one province. It would be assumed that all the supplies purchased locally are delivered to the close supply node (L) by some other means and are not part of our planning problem.

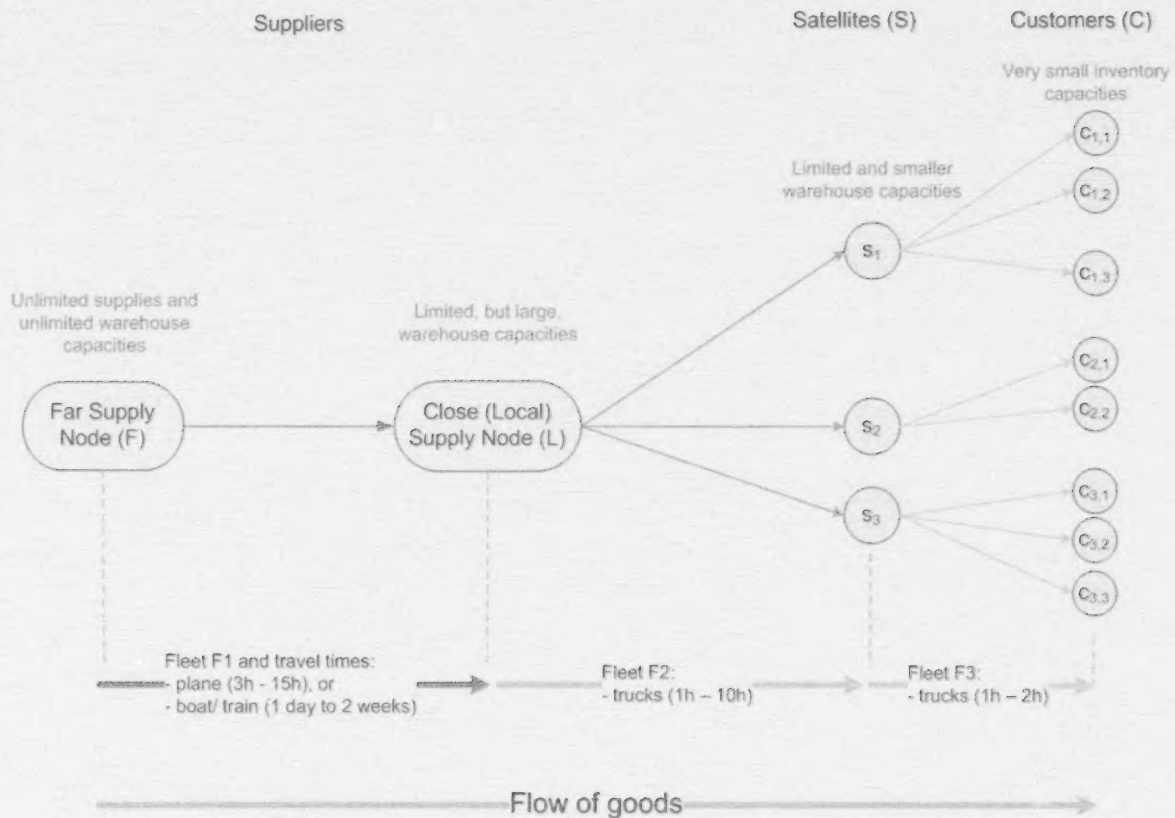


Figure 3-1 The three-echelon Supply Chain Network
(The arrows are showing from where the supplies/goods are coming.)

3.2 Problem Definition and Characterization

When you face a complex problem, it is quite natural to address first a simplified variant and move on from there. The same approach is taken here: the deterministic variant is considered first, before addressing the full complexity of the problem with stochastic demand. Thus, in the deterministic model we assume that demands are known in advance, and in the stochastic model we assume that we know possible scenario realizations of the uncertain demand.

The problem characteristics include:

- Different modes of transportation
- Vehicle fleet
 - Separate vehicle fleets between any two echelons
 - Heterogeneous vehicle fleets in each echelon
 - Depots
 - Vehicle capacities
 - Re-fueling issues

- Compatibility between vehicles and supply types
- Compatibility between two supplies travelling on the same vehicle, for each vehicle type
- Routes
 - Each route starting at the far supply node (F) visits the close supply node (L) and comes back to the far supply node.
 - Each route starting at the close supply node (L) visits one or more satellite nodes and comes back to the close supply node (L). Each satellite node can be visited at most once in each route.
 - Each route starting at a satellite visits one or more demand nodes and comes back to the satellite. Each demand node can be visited at most once in each route. Each demand node is assigned to one satellite. Each satellite node can serve only the demand nodes assigned to it.
- Demand
 - Demands for each time period: deterministic and stochastic. Each demand is associated with the time period and it can be assumed that the supply has to arrive and be in the inventory at the demand node at the end of the previous time period so that it can be consumed and it can satisfy the demand. There is no time window explicitly associated with the demand.
 - Different types of supplies, some requiring specialized transportation assets.
- Inventories/ Stores
 - Inventories (stores) at each location
 - Different types of inventories (stores) at one location
 - Compatibility between store and supply types
 - Different cost of inventories at each echelon or at each location
- Travel times
 - Deterministic
- Service times and Loading/ Unloading times
 - Service times may vary at each node
 - Unloading/ Loading proportional to the quantities transported
- Transportation networks: each edge has
 - Distance
 - Cost (associated with mileage, time, fuel, journey, load, and potentially safety)

Problem characteristics that could be stochastic:

- Demand

We considered the most commonly used metrics including:

- Inventory costs
- Transportation costs
- Service level, *i.e.*, unmet demand

The characteristics of our supply chain management problem and model that are novel compared to the state-of-the-art literature include:

- Inventories at each node of the SCN.
- Transportation times in the first level of the SCN are measured in weeks, while the travel times in the other levels of the SCN are measured in hours or minutes, resulting in the situation that this portion of the network must be handled in a particular way, when compared to the rest of the network, due to this different time scale.
- Integration of inventory management in a multi-echelon vehicle routing problem.
- Multiple realistic problem characteristics – multiple products, heterogeneous fleet, multiple periods, compatibility constraints – that have been considered separately in various multi-echelon VRP or SCM models, but never simultaneously in the same problem.
- Stochastic demand.
- Heterogeneous fleets of vehicles at each echelon.

Other problem characteristics:

- Demand for food, water, and fuel is much more predictable than demand for medical supplies.
- Some supplies require specialized transportation assets.

Table 3-1 compares the characteristics of different logistics applications.

Table 3-1 Logistics Scenario Examples and Their Similarities and Differences

Logistics Scenarios Examples	Tight constraints	Objectives	Vehicle Fleet	Network	Stochastic	Fluctuating Demand
Commercial/Retail	Vehicle fleet Warehouse capacities	Min cost	Fixed size Homogenous	Stable and predictable travel times	Demand Travel times	Yes, but not very high variability
Mega-Earthquake	Supplies (medical, water, food) Transportation network Warehouse capacities; gradually decreasing from left to right in the SCN	Min risk Min losses of supplies	Not tight constraint Heterogeneous	Variable travel times Risks Not entire network available	Demand Travel times Lost supplies Risks	High variability
Man-made disaster: virus spread/disease outbreak	Supplies (medical) Warehouse capacities	Min risk Min losses of supplies	Not tight constraint Heterogeneous	Variable travel times Risks	Demand Travel times Lost supplies Risks	High variability
Peace-keeping	Supplies (fuel, equipment, medical) Transportation network Warehouse capacities	Min risk Min losses of supplies	Not tight constraint Heterogeneous	Variable travel times Risks Not entire network available	Demand Travel times Lost supplies Risks	High variability

3.3 SCM in Disaster Relief Operations

The following are the characteristics of the deterministic problem considering the disaster relief scenario:

- Objective is the weighted sum of:
 - Transportation costs for Echelon 0 – from the far supply node (F) to the close supply node (L)
 - Transportation costs for Echelon 1 – from the close supply node (L) to the satellite nodes
 - Transportation costs for Echelon 2 – from the satellite nodes to the customer nodes
 - Inventory costs
 - Unmet demand penalties
- General problem characteristics:
 - Centralized distribution strategy
 - The number of time periods and their duration
- The structure of the supply chain network is shown in Figure 3-1:
 - One far supply node F
 - One close (local) supply node L
 - A number of satellite nodes, $S = \{s_1, s_2, \dots, s_k\}$
 - A number of customer nodes with demand for each supply node i , $C_i = \{c_{i1}, c_{i2}, \dots, c_{im}\}$
- Multi-products:
 - Fuel
 - Water
 - Food
 - Medication
 - Medication requiring refrigeration
 - Food requiring refrigeration
- Inventories: there are three types of warehouses/ inventories at each node of the SCN, and there is a maximum capacity for each warehouse type at each node:
 - Fuel warehouse
 - Regular warehouse: Water, food, medication
 - Specialized warehouse: Refrigerator for special medication and food

- Types of transportation assets:
 - Special assets for transport of fuel
 - General assets for transport of packaged water, food, and medication
 - Refrigerated transportation assets for special medication and food
- Fleets of transportation assets:
 - Fleet F1 – for the transportation within the SCN first level – between F and L. The fleet depot is located at F. There are two modes of transportation, both with large capacities:
 - Planes: fast, expensive, not very many in the fleet
 - Ships or trains: slower and cheaper mode of transportation with relatively large fleet, with the capacities much larger than planes
 - Fleet F2 – for the transportation within the SCN second level – between L and the satellite nodes in S. The fleet depot is located at L. There are three types of vehicles: Fuel trucks, regular trucks (for palleted goods), and specialized trucks (refrigerators) with medium capacities.
 - Fleet F3 – for the transportation within the SCN third level – between the satellite nodes in S and the customer nodes in C. There is one depot at each satellite node. There are also three types of vehicles: Fuel trucks, regular trucks (for palleted goods), and specialized trucks (refrigerators) with smaller capacities.
- Multi-period problem – the planning horizon is divided in several time periods that are used to synchronize the transportation between the SCN levels that have different travel times. Having decisions variables for each time period in an integrated model, assures that the decisions in one period take into account the decisions and expected outcomes from the previous period.
- Travel times:
 - Each routes between L and satellites in S, and routes between satellites and customers in C can be completed in the same time period within which it starts.
 - The speed is provided for each transportation asset, and the travel times along each link are calculated based on its length.
- Demand/ consumption:
 - There is a demand/ consumption for each product at each customer node in C for each period.
 - (Optional) We can also consider that there is a demand for each product at the close supply node L and at each satellite node.
- Supply origins:
 - The supplies are coming from the far supply node F.
 - We assume that the supplies and capacities of warehouses at the far supply node F are unlimited.
 - The supplies may have their origin at the close supply node L.

- Transportation routes:
 - First level routes – F to L – Fleet F1:
 - Direct routes between the far supply node F and the close supply node L.
 - Second level routes – L to S – Fleet F2:
 - A vehicle from fleet F2 starts its route at the close supply node and visits each satellite node at most once before returning to the close supply node.
 - Each route starts and finishes at the close supply node L and can visit several satellite locations.
 - Split deliveries to a satellite are allowed, *i.e.*, a portion of its demand can be filled with one truck (route) and the remaining portion can be filled with another truck (route).
 - Third level routes – S to C – fleet F3:
 - Each route starts and finishes at some satellite and can visit several customer locations.
 - Each satellite has its subset of customers. No customer is served by two or more satellite locations.
 - Split deliveries are allowed due to demand for multiple products.
 - Multi-trip routes for one vehicle are allowed at this level.

The transportation assets from fleet F1 can travel only between the far supply node F and the close supply node L. The vehicles from fleet F2 can visit only the close supply node L and the satellite nodes from S. The vehicles from fleet F3 can visit only the nodes in S and C. Each satellite has its own fleet F3 assigned to it.

3.4 Assumptions

This section lists the main assumptions of our supply chain management problem:

1. Distribution Network Structure is given: the number and location of the SCN nodes.
2. Distribution strategy is centralized.
3. The following logistics activities will not be considered:
 - Recovery of damaged vehicles
 - Urgent direct flights from the supply nodes (F or L) to customer nodes
 - Hazardous material transport
 - Vehicle unavailability due to repair
 - Repair duration
 - Fleet size decrease due to assignment to other activities
4. The problems that are not considered:
 - Bin packing for filling up the vehicles/ aircrafts, *i.e.*, planning of the loading of packages into trucks/ aircrafts.
 - Scheduling and routing of protection support vehicles and staff.

4 Literature Review

4.1 Humanitarian Logistics

The papers have been divided into two groups. The first group of papers does not provide rigorous models and sometimes does not provide explicit statements of the optimization problems, but deals with analysis of the issues and different policy aspects involved with humanitarian logistics. These policy papers could be used when generating the problem instances because they often provide statistical data relevant to operational problems in the humanitarian logistics.

[Kovacs and Spens, 2007], [Martinez et al, 2011], [VanWassenhove et al, 2012] discuss humanitarian logistic at a very high level and provide global views and analysis of the issues and policies without providing a model or a solution approach. [Martinez et al, 2011] provides data on humanitarian vehicle fleet, routing, maintenance, etc. The data might be used for generating random problem instances.

The second group of papers provides rigorous modeling potentially with mathematical programming formulations of the problem.

[Najafi et al, 2013] deals with a multi-objective robust optimization model for logistics planning in the earthquake response phase. The problem is multi-periods and multi-products. The SCN consists of the demand nodes, the supply nodes, and the nodes representing the emergency medical centers. The vehicle fleet is characterized by different modes of transport and different capacities with both weight and volume capacities. Demand has priorities. The transportation of people is also considered, and it does not allow mixing of commodities and people. The uncertainty is in the number of injured people, commodity demands, suppliers' capacities, and hospitals' capacities. The uncertain data is dealt with by an uncertain set defined by a nominal value and a permitted change. These sets can be unequal for different periods as they can follow from non-identical distributions.

[Doyen et al, 2012] present a two-echelon stochastic facility location model for humanitarian relief logistics and uses a two-stage stochastic programming model. Decisions are made for the location of the pre- and post-disaster rescue centers, the amount of relief items to be stocked at the pre-disaster rescue centers, and the amount of relief item flows at each echelon. The objective is to minimize the total cost of facility location, inventory holding, transportation and shortage. The deterministic equivalent of the model is a mixed-integer linear programming model which is solved by a heuristic method based on Lagrangean relaxation. For the experimental study, randomly generated test instances are used with up to 25 scenarios. The model is validated by calculating the value of the stochastic solution and the expected value of perfect information.

[Nikbakhsh et al, 2011] discusses the humanitarian logistics planning in disaster relief operations. It provides the classification of disasters, occurrence statistics (1900-2005), distribution by type, and statistics of damages in China, India, Iran, and US. It also lists the world's five most important industrial accidents. The authors present the disaster management cycle, and discuss the differences and similarities between the humanitarian logistics and the commercial supply chain. For humanitarian logistics, the paper provides the humanitarian logistics supply chain structure and the list of goods.

Very simple separate Mixed-Integer Programming solutions (MIPs) are presented for: the facility location problem, the transportation and distribution problem (simple Vehicle Routing Problem (VRP)),

and the inventory problem (deterministic multi-period model with multi-objective function). Also, an integrated location-routing model is presented. The paper also proposes performance measures for a humanitarian logistics system. Case-studies are also presented: analysis of weaknesses of response logistics in the last few disasters (Katrina, Asian Tsunami, earthquake in 2006).

4.2 Two-Echelon Vehicle Routing Problem

We searched for papers on two-echelon vehicle routing problems since they more often contain rigorous modeling, mathematical programming formulations, and solution approaches for the relevant optimization problems.

Again, the papers were divided into two groups. The first group of papers discusses the heuristics approaches without introducing the MIP formulation of the problems, while the second group of papers provides MIP formulations.

[Jacobsen and Madsen, 1980] is interesting from a historical perspective since it represents the first time a two-echelon VRP was addressed. The problem was:

- Location (two-echelon) vehicle routing problem.
- Distribution of newspapers via transfer points.
- Combined routing problem and location problem.
- Location of satellite nodes is to be determined.
- No split deliveries on the routes between the depot and satellites.

The solution approach presented is a simple heuristic for assignment of customers to satellites and route construction.

The characteristics of the introduced problem that are different from our problem:

- The combined routing problem and location problem.
- No inventory management.
- One product.
- No split deliveries on the routes between the depot and satellites.

[Crainic et al, 2008] describes the static and deterministic two-echelon vehicle routing problem with the following characteristics:

- Objective: Minimize the total traveling costs.
- SCN network: One depot, multiple satellites, multiple customers.
- Demand and warehouses: One product. No warehouses.
- Fleet: Different types of vehicles at each echelon.

- Routes: Split deliveries are allowed on the routes from the depot to the satellites, but not on the routes from satellites to customers.

The proposed solution approach includes:

- No mathematical programming model.
- Depot-to-satellite (first-level) and satellite-to-customer (second-level) deliveries are divided into two separate sub-problems.
- At the second-level, customers are clustered and assigned to satellites with heuristic rules. It leads to multiple independent single depot VRPs (one for each satellite) which are solved exactly with ILOG dispatcher. Then, at the first-level, the obtained VRP is also solved with ILOG dispatcher.
- Another variant is proposed by directly solving a multi-depot VRP at the second level.
- At the end, exchange heuristics are applied to improve the solution.

The characteristics of the introduced problem that are different to our problem:

- There is no inventory management.
- One product considered.

Subsequently, several papers address the same problem with improved heuristics approaches:

- [Crainic et al, 2008] This is an extended abstract that describes lower bounds for the first-level and second-level sub-problems (for example, by relaxing vehicle capacity). These bounds can be used to evaluate the performance of heuristic methods.
- [Crainic et al, 2010] Analysis of solutions produced by the clustering heuristic reported in Crainic et al. (2008) depending on the number of customers and satellites and their spatial distribution.
- [Crainic et al, 2011a] Multi-start local search heuristic. Starting with an assignment of customers to satellites, a local search heuristic is used to find better assignments. The local search is restarted through a perturbation of the best assignment found so far. VRPs are (heuristically) solved with a branch-and-cut algorithm which is stopped after some given Central Processing Unit (CPU) time.
- [Crainic et al, 2012] Different assignments of customers to satellites are built with GRASP using a randomized variant of the clustering heuristic reported in [Crainic et al, 2008]. The obtained VRPs are solved with the hybrid meta-heuristic EVE-OPT, previously proposed by Perboli et al. (2008).
- [Hemmelmayr et al, 2012] proposed an Adaptive Large Neighborhood Search (ALNS), and introduced a new set of benchmark instances with up to 10 satellites and 200 customers.

[Jung and Mathur, 2007] introduced the problem where inventory and distribution decisions are considered jointly. The problem solution consists of the replenishment quantities, the associated replenishment (reorder) intervals for each retailer, and the delivery routes. The solution approach is a heuristic. The problem characteristics are:

- One warehouse and n retailers with constant demand

- Inventories at the warehouse and at retailers
- Objective: Minimize the long-run average inventory and the transportation costs

[Mancini, 2012] is a summary of Mancini's Ph.D. thesis on heuristic methods for solving the two-echelon VRP. Difference: no inventory management has been considered.

The following group of papers provide MIP formulations of their respective problems.

[Crainic et al, 2009] describes a two-echelon VRP in a city logistics context. They provide a mathematical model for a time-dependent variant with fleet synchronization at satellites and customer time windows. There is no algorithm proposed for solving the problem. Difference: no inventories, cross-docking.

[Gonzalez-Feliu et al, 2006] describes a flow-based mathematical programming model for the two-echelon capacitated vehicle routing problem. The authors also propose valid inequalities (cuts) that were used when the model is solved with an MIP solver (Xpress). A set of problem instances with up to 4 satellites and 50 customers was proposed. The medium-sized instances with 2 satellites and 21 customers are solved to optimality.

[Jepsen et al, 2013] propose a branch and cut algorithm for the symmetric capacitated two-echelon VRP. In their model the satellite nodes can be left unused. The objective is to minimize the traveling costs plus the handling costs at the satellites. The authors propose a new mathematical programming model for the two-echelon VRP, and another model for a relaxed version of the two-echelon VRP which breaks the symmetry of the first model and provides tighter lower bounds when linear relaxations are solved. The authors mention that the model in [Perboli et al, 2011] has a mistake and provide an example to support their claim. The branch-and-cut algorithm is applied on the relaxed model. When an integer solution is found, it is checked for feasibility to the two-echelon VRP. If infeasible, a specialized branching scheme is applied. Linear relaxations are solved with CPLEX. The proposed exact algorithm can solve instances with up to 5 satellites and 50 customers. Difference: no inventories.

[Perboli and Tadei, 2010] and [Perboli et al, 2011] strengthen the MIP mathematical programming model proposed by [Gonzalez-Feliu et al, 2006] by adding new valid inequalities.

For [Gonzalez-Feliu et al, 2006], [Perboli and Tadei, 2010], [Perboli et al, 2011], and [Gonzalez-Feliu et al, 2006], the differences compared to our problem are:

- No inventory management
- No scheduling issues
- One product
- No warehouses (inventories) at satellites
- Homogeneous vehicles for each level

[Santos et al, 2013] considers the same two-echelon vehicle routing problem but addresses it with a branch-and-price approach.

4.3 Integrated SCM Problems

Most of the literature on the integrated problem in the supply chain management deals with network design with some limited routing considerations – the location-routing problems. However, some recent studies report on the integration of inventory management and routing.

[Mumtaz and Brah, 2010] studied the integrated location and inventory problem in a two-echelon SCN. The problem consists of finding the number and location of distribution centers (satellites) that will be used for serving a set of customers with a given (deterministic) demand for product made in one factory. Shortages are not allowed. The location of factory and customers is known. The authors proposed an MIP formulation of the problem and solved the problem using a heuristic. Vehicle routing is not explicitly considered. The objective is to minimize long run average total costs consisting of the location costs, transportation costs, and inventory holding costs. Differences from our problem: we do not have the network design and location problem. Also, they are assuming:

- Unlimited inventory capacities at the plant and distribution centers
- Unlimited vehicle capacities for the vehicles transporting goods between the plant and the distribution centers
- Homogenous fleet of vehicles
- One product
- No vehicle routing problem explored explicitly with all its issues

[Max Shen, 2007] is a survey paper on supply chain models dealing with the decisions on the inventory locations and the distribution and routing. There are mathematical programming formulations of different problems that are built progressively from easier to more complex.

[Anily and Federgruen 1993] dealt with the two-echelon distributions systems with vehicle routing costs and central inventories. The problem is static, deterministic, and characterized by one depot and multiple retailers with inventories at the depot and retailers. Difference: One product. There is no useful mathematical programming model. The proposed heuristic partitions the retailers into regions (super-retailers), reducing the problem to finding an inventory replenishment strategy for a classical one-depot – multiple retailers system. The retailers in the same region are visited by a single vehicle route.

[Jung, 2012] proposes an effective genetic algorithm for solving the integrated inventory and routing problem of supply chain composed of multi-warehouses and multi-retailers. The objective is to determine replenishment intervals for the retailers and warehouses as well as the vehicles routes so that the total cost of delivery and inventory cost is minimized. Evaluating the fitness of the objective function has a computational complexity close to linear.

[Dondo et al, 2011] extends previous work – [Dondo et al, 2009] dealing with management of distribution within a supply chain network – by including cross-docking. Thus, inventories and cross docking at intermediate facilities are both allowed. The problem is static and deterministic. This work is the most similar to ours. In some ways, it extends our problem by allowing direct shipping from suppliers to customers and by considering the allocation of vehicles to facilities. In other ways, it is more restrictive by considering a single time period. A mathematical model is provided and solved with

an MIP solver (GUROBI). Tests on five instances derived from case studies with up to 3 satellites, 29 customers and 6 products are reported. Difference: direct shipping, no far supply node, no inventory at customer nodes, single time period.

5 Model: 3E-SCM

Clearly, addressing the full complexity of our problem is a challenging task. For example, the two-echelon vehicle routing problem is a simpler problem but has only been recently addressed in the literature. The complexity of our problem comes from different dimensions such as demand for multiple products, the presence of a heterogeneous fleet of vehicles, inventories, and multiple periods. We also have an additional level made of a unidirectional link between a far supply node and a close supply node. This link must be handled in a particular way, when compared to the rest of the network, due to a different time scale. All these issues make for a novel problem that has not been previously considered in the literature.

For the sake of a comparison with recent studies, among the most comprehensive papers dealing with multi-period, multi-objective, and multi-commodity humanitarian logistics optimization we select [Najafi et al, 2013] which unfortunately does not include intermediate transportation nodes (called satellites in our problem) but does handle the inventory management problem explicitly.

The main contribution and novelty anticipated in our project is the explicit integration of the transportation (distribution) management problem and the inventory management problem for the two-echelon or three-echelon supply chain networks.

In this section, we model the centralized, static, deterministic supply chain management problem within a three-echelon network. The network design is known and we are considering the problem of inventory management and the problem of distribution management (vehicle routing).

5.1 Deterministic Model: Mathematical Programming Formulation

This section presents the deterministic model of the Three-Echelon SCM problem with centralized inventory and distribution management.

The problem has five objective criteria, one of which is a penalty function. The criteria are:

- Transportation costs for Echelon 0 – from the far supply node (F) to the close supply node (L)
- Transportation costs for Echelon 1 – from the close supply node (L) to the satellite nodes
- Transportation costs for Echelon 2 – from the satellite nodes to the customer nodes
- Inventory costs
- Unmet demand penalties

The multiple criteria are dealt with by using an objective that is the weighted sum of the five listed criteria. The sum of the first four weights could be equal to 1, and the weight of the last criteria ω_5 is usually set to a large number to avoid an unmet demand. In the situations when an unmet demand is

allowed and the decision maker is more concerned with minimizing the costs, this fifth weight ω_5 can be reduced. The right value for this weight can be evaluated after computational experiments and consultations with experts and decision makers. However, note that the high values for ω_5 are appropriate in order to address the “non-comparable” criteria contributions (*e.g.* travel cost vs. unmet demands proportion).

Notation

N	set of nodes
A	set of arcs
L	close (local) supply node
F	far supply node
S	set of satellites
S^+	$S \cup \{L\}$
C	set of customers
C_s	set of customers served by satellite $s \in S$
C_s^+	$C_s \cup \{s\}$
B	set of bases (NVC)
T	set of time periods (planning horizon)
η^{\max}	duration of a time period – this is also the maximum duration of all routes of one vehicle within a time period
\bar{t}	last period among the time periods in T
P	set of product types
G	set of store types
G_j	set of store types at node $j \in N$. It is assumed that there is only one store per store type at each node in the distribution network
R_g	set of product types compatible with store type $g \in G$.
a_g^p	$=1$ when $p \in R_g$, 0 otherwise. This is the indicator parameter indicating the compatibility between the product type and the store type
V	set of vehicle types
V_b	set of vehicle types at base $b \in B$
P_v	set of product types compatible with vehicle type $v \in V$
b_v^p	$=1$ when $p \in P_v$, 0 otherwise. This is the indicator parameter indicating the compatibility between the product type and the vehicle type
n_{vb}	number of vehicles of type $v \in V$ at base $b \in B$
m_{vs}	maximum number of routes of vehicle type $v \in V$ from satellite $s \in S$ during one time period
d_{pc}^t	demand of product type $p \in P$ of customer $c \in C$ in period $t \in T$
τ_{ijv}	travel time on arc $(i, j) \in A$ for vehicle type $v \in V$; This is equal to the length of arc (i, j) divided by the speed the vehicle v can use on the arc (i, j) : $\text{length}_{ij} / \text{speed}_{ijv}$

c_{ijv}	travel cost on arc $(i,j) \in A$ for vehicle type $v \in V$; This is equal to the length of arc (i,j) multiplied by the fuel consumption per unit of length of vehicle type v on the arc (i,j) multiplied by the fuel cost per unit of fuel: $\text{length}_{ij} * \text{fuel_consumption}_v * \text{fuel_cost}$
f_g^p	inventory cost per unit of product type $p \in R_g$ per time period at store type $g \in G$ at customer node
\tilde{f}_g^p	inventory cost per unit of product type $p \in R_g$ per time period at store type $g \in G$ at satellite node
\hat{f}_g^p	inventory cost per unit of product type $p \in R_g$ per time period at store type $g \in G$ at the close supply node
ρ_{vs}^p	loading/unloading time of one unit of product type $p \in P$ at satellite $s \in S$ for vehicle type $v \in V$
δ_v	number of time periods to deliver from F to L for vehicle type $v \in V$. This is equal to the length of arc (F,L) divided by the speed of vehicle type v along this arc: $\text{length}_{FL} / \text{speed}_{FLv}$.
ϕ_v	delivery cost from F to L for vehicle type $v \in V$. This is equal to the length of arc (F,L) multiplied by the fuel consumption per unit of length of vehicle type v multiplied by the fuel cost per unit of fuel: $\text{length}_{FL} * \text{fuel_consumption}_v * \text{fuel_cost}$. An additional fixed cost can be added, because the transportation assets used on this leg are major assets including planes, ships, and railcars.
ϵ_v	number of time periods of unavailability after delivery from F to L for vehicle type $v \in V$. Equal to the time needed for the vehicle (transportation asset) to come back from the close supply node L to the far supply node F plus the maintenance time needed after each trip.
σ_{iv}	service time at node $i \in N$ for vehicle type $v \in V$. This time is equal to the time needed for potential re-fueling, (potential) quick check-up, and administrative activities.
τ_v^{\max}	maximum route duration for vehicle type $v \in V$ – this can be used for handling re-fueling issues
u_v	capacity of vehicle type $v \in V$
\bar{u}_g	capacity of store type $g \in G$
ω_l	weights in the objective function, $l = 1, 2, 3, 4, 5$
$\gamma_v^{pp'}$	$= 1$ if product types $p \in P$, $p' \in P$, $p \neq p'$, can be transported together (at the same time, on the same vehicle) by vehicle type v ; 0 otherwise
$s(c)$	satellite for customer $c \in C$
α_{pc}	penalty for not satisfying the demand for product p at customer c , i.e., priority for satisfying the demand for product p at customer c
μ	small number $0 < \mu < 1$ to accommodate the loads q between 0 and 1

Decision variables

- x_{ijkvs}^{rt} = 1 if the r^{th} route of the k^{th} vehicle of type v of satellite s travels from i to j in time period t for $i, j \in C_S^+$, $i \neq j$, $k = 1, \dots, n_{vs}$, $v \in V_s$, $s \in S$, $r = 1, \dots, m_{vs}$, $t \in T$; 0 otherwise.
- \tilde{x}_{ijkv}^t = 1 if the k^{th} vehicle of type v of close supply node L travels from i to j in time period t for $i, j \in S^+$, $i \neq j$, $k = 1, \dots, n_{vL}$, $v \in V_L$, $t \in T$; 0 otherwise.
- \hat{x}_{kv}^t = 1 if the k^{th} vehicle of type v of remote supply node F is sent to close supply node L in time period t , $k = 1, \dots, n_{vF}$, $v \in V_F$, $t \in T$; 0 otherwise.
- y_{kvs}^{prt} = 1 if the r^{th} route of the k^{th} vehicle of type v of satellite s is used to transport product p in time period t for $k = 1, \dots, n_{vs}$, $v \in V_s$, $s \in S$, $p \in P_v$, $r = 1, \dots, m_{vs}$, $t \in T$; 0 otherwise.
- \tilde{y}_{kv}^{pt} = 1 if the k^{th} vehicle of type v of close supply node L is used to transport product type p in time period t for $k = 1, \dots, n_{vL}$, $v \in V_L$, $p \in P_v$, $t \in T$; 0 otherwise.
- \hat{y}_{kv}^{pt} = 1 if the k^{th} vehicle of type v of remote supply node F is sent to close supply node L with product type p in time period t for $k = 1, \dots, n_{vF}$, $v \in V_F$, $p \in P_v$, $t \in T$; 0 otherwise.
- $q_{kvcs(c)}^{prt}$ quantity of product type p delivered to customer c on the r^{th} route of the k^{th} vehicle of type v of satellite $s(c)$ in time period t , for $k = 1, \dots, n_{vs(c)}$, $v \in V_{s(c)}$, $c \in C$, $p \in P_v$, $r = 1, \dots, m_{vs(c)}$, $t \in T$.
- \tilde{q}_{kvs}^{pt} quantity of product type p delivered to satellite s by the k^{th} vehicle of type v of close supply node L in time period t , for $k = 1, \dots, n_{vL}$, $v \in V_L$, $s \in S$, $p \in P_v$, $t \in T$.
- \hat{q}_{kv}^{pt} quantity of product type p sent to close supply node L by the k^{th} vehicle of type v of remote supply node F in time period t , for $k = 1, \dots, n_{vF}$, $v \in V_F$, $p \in P_v$, $t \in T$.
- $h_{gcs(c)}^{pt}$ inventory level of product type $p \in R_g$ in store type $g \in G_c$ at customer node c (of the satellite node $s(c)$) at the beginning of period $t \in T$. Note that $h_{gcs(c)}^{p0}$ should be fixed and equal to the initial inventory levels if those are known in advance.
- \tilde{h}_{gs}^{pt} inventory level of product type $p \in R_g$ in store type $g \in G_s$ at satellite node s at the beginning of period $t \in T$. Note that h_{gs}^{p0} should be fixed and equal to the initial inventory levels.
- \hat{h}_g^{pt} inventory level of product type $p \in R_g$ in store type $g \in G_L$ at the close supply node L at the beginning of period $t \in T$. Note that h_g^{p0} should be fixed and equal to the initial inventory levels.
- $w_{kvcs(c)}^{rt}$ position of customer c in the r^{th} route of the k^{th} vehicle of type v of satellite $s(c)$ in time period t for $k = 1, \dots, n_{vs(c)}$, $v \in V_{s(c)}$, $c \in C$, $r = 1, \dots, m_{vs(c)}$, $t \in T$.
- \tilde{w}_{kvs}^t position of satellite s in the route of the k^{th} vehicle of type v of close supply node L in time period t for $k = 1, \dots, n_{vL}$, $v \in V_L$, $s \in S$, $t \in T$.
- \underline{d}_{pc}^t amount of unsatisfied demand of product p at customer c in time period t .

Objective

$$\begin{aligned}
\text{Min } \sum_{t \in T} \left(\omega_1 \sum_{s \in S} \sum_{v \in V_s} \sum_{k=1}^{n_{vs}} \sum_{r=1}^{m_{vs}} \sum_{i \in C_s^+} \sum_{\substack{j \in C_s^+ \\ i \neq j}} c_{ijv} x_{ijkvs}^t + \omega_2 \sum_{v \in V_L} \sum_{k=1}^{n_{vL}} \sum_{s \in S^+} \sum_{\substack{s' \in S^+ \\ s \neq s'}} c_{ss'v} \tilde{x}_{ss'kv}^t \right. \\
+ \omega_3 \sum_{v \in V_F} \sum_{k=1}^{n_{vF}} \varphi_v \hat{x}_{kv}^t \\
+ \omega_4 \left(\sum_{s \in S} \sum_{c \in C_s} \sum_{g \in G_c} \sum_{p \in R_g} f_g^p h_{gcs(c)}^{pt} + \sum_{s \in S} \sum_{g \in G_s} \sum_{p \in R_g} \tilde{f}_g^p \tilde{h}_{gs}^{pt} \right. \\
\left. + \sum_{g \in G_L} \sum_{p \in R_g} \hat{f}_g^p \hat{h}_g^{pt} \right) + \omega_5 \sum_{p \in P} \sum_{c \in C} \alpha_{pc} d_{pc}^t \Big)
\end{aligned}$$

Constraints

Inventory balance at customer nodes

$$\sum_{g \in G_c} h_{gcs(c)}^{pt} + \sum_{v \in V_{s(c)}} \sum_{k=1}^{n_{vs(c)}} \sum_{r=1}^{m_{vs(c)}} q_{kvcs(c)}^{prt} - d_{pcs(c)}^t = \sum_{g \in G_c} h_{gcs(c)}^{p(t+1)} - d_{pcs(c)}^t, \quad (1)$$

$c \in C_s, s \in S, p \in P, t \in T \setminus \{\bar{t}\}.$

Inventory balance at customer nodes for the last period \bar{t} in the planning horizon

$$\sum_{g \in G_c} h_{gcs(c)}^{p\bar{t}} + \sum_{v \in V_{s(c)}} \sum_{k=1}^{n_{vs(c)}} \sum_{r=1}^{m_{vs(c)}} q_{kvcs(c)}^{pr\bar{t}} - d_{pcs(c)}^{\bar{t}} \geq -d_{pcs(c)}^{\bar{t}}, \quad c \in C_s, s \in S, p \in P. \quad (2)$$

Inventory balance at satellites

$$\sum_{g \in G_s} \tilde{h}_{gs}^{pt} + \sum_{v \in V_L} \sum_{k=1}^{n_{vL}} \tilde{q}_{kvs}^{pt} - \sum_{c \in C_s} \sum_{v \in V_s} \sum_{k=1}^{n_{vs}} \sum_{r=1}^{m_{vs}} q_{kvcs(c)}^{prt} = \sum_{g \in G_s} \tilde{h}_{gs}^{p(t+1)}, \quad s \in S, p \in P, t \in T \setminus \{\bar{t}\}. \quad (3)$$

Inventory balance at satellites for the last period \bar{t} in the planning horizon

$$\sum_{g \in G_s} \tilde{h}_{gs}^{p\bar{t}} + \sum_{v \in V_L} \sum_{k=1}^{n_{vL}} \tilde{q}_{kvs}^{p\bar{t}} - \sum_{c \in C_s} \sum_{v \in V_s} \sum_{k=1}^{n_{vs}} \sum_{r=1}^{m_{vs}} q_{kvcs(c)}^{pr\bar{t}} \geq 0, \quad s \in S, p \in P. \quad (4)$$

Inventory balance at close supply node L

Note that during the implementation when $t - \delta_v < 0$, assume $\hat{q}_{kv}^{p(t-\delta_v)} = 0$ in the second term

$$\sum_{g \in G_L} \hat{h}_g^{pt} + \sum_{v \in V_F} \sum_{k=1}^{n_{vF}} \hat{q}_{kv}^{p(t-\delta_v)} - \sum_{s \in S} \sum_{v \in V_L} \sum_{k=1}^{n_{vL}} \tilde{q}_{kvs}^{pt} = \sum_{g \in G_L} \hat{h}_g^{p(t+1)}, \quad p \in P, t \in T \setminus \{\bar{t}\}. \quad (5)$$

Inventory balance at close supply node L for the last period \bar{t} in the planning horizon

$$\sum_{g \in G_L} \hat{h}_g^{p\bar{t}} + \sum_{v \in V_F} \sum_{k=1}^{n_{vF}} \hat{q}_{kv}^{p(\bar{t}-\delta_v)} - \sum_{s \in S} \sum_{v \in V_L} \sum_{k=1}^{n_{vL}} \tilde{q}_{kvs}^{p\bar{t}} \geq 0, \quad p \in P. \quad (6)$$

Demand constraints at customer nodes

$$\sum_{g \in G_c} h_{gcs(c)}^{pt} \geq d_{pcs(c)}^t - \underline{d}_{pcs(c)}^t, \quad c \in C_s, s \in S, p \in P, t \in T. \quad (7)$$

Demand constraints at satellites

$$\sum_{g \in G_s} \tilde{h}_{gs}^{pt} \geq \sum_{c \in C_s} \sum_{v \in V_s} \sum_{k=1}^{n_{vs}} \sum_{r=1}^{m_{vs}} q_{kvcs(c)}^{prt}, \quad s \in S, p \in P, t \in T. \quad (8)$$

Demand constraints at close supply node L

$$\sum_{g \in G_L} \hat{h}_g^{pt} \geq \sum_{s \in S} \sum_{v \in V_L} \sum_{k=1}^{n_{vL}} \tilde{q}_{kvs}^{pt}, \quad p \in P, t \in T. \quad (9)$$

Store capacity constraints at customer nodes

$$\sum_{p \in R_g} h_{gcs(c)}^{pt} \leq \bar{u}_g, \quad g \in G_c, c \in C_s, s \in S, t \in T. \quad (10)$$

Compatibility between store types and product types at customer nodes

$$h_{gcs(c)}^{pt} \leq a_g^p \bar{u}_g, \quad p \in P, g \in G_c, c \in C_s, s \in S, t \in T. \quad (11)$$

Store capacity constraints at satellite nodes

$$\sum_{p \in R_g} \tilde{h}_{gs}^{pt} \leq \bar{u}_g, \quad g \in G_s, s \in S, t \in T. \quad (12)$$

Compatibility between store types and product types at satellite nodes

$$\tilde{h}_{gs}^{pt} \leq a_g^p \bar{u}_g, \quad p \in P, g \in G_s, s \in S, t \in T. \quad (13)$$

Store capacity constraints at the close supply node

$$\sum_{p \in R_g} \hat{h}_g^{pt} \leq \bar{u}_g, \quad g \in G_L, t \in T. \quad (14)$$

Compatibility between store types and product types at the close supply node

$$\hat{h}_g^{pt} \leq a_g^p \bar{u}_g, \quad p \in P, g \in G_L, t \in T. \quad (15)$$

Product compatibility constraints aboard the vehicles (between satellites and customers)

$$y_{kvs}^{prt} + y_{kvs}^{p'rt} \leq 1 + \gamma_v^{pp'}, \quad (16)$$

$$k = 1, \dots, n_{vS}, v \in V_S, s \in S, p \in P_v, p' \in P_v, p \neq p', r = 1, \dots, m_{vS}, t \in T.$$

Product compatibility constraints aboard vehicles (between L and satellites)

$$\tilde{y}_{kv}^{pt} + \tilde{y}_{kv}^{p't} \leq 1 + \gamma_v^{pp'}, \quad k = 1, \dots, n_{vL}, v \in V_L, p \in P_v, p' \in P_v, p \neq p', t \in T. \quad (17)$$

Product compatibility constraints in vehicles (between F and L)

$$\hat{y}_{kv}^{pt} + \hat{y}_{kv}^{p't} \leq 1 + \gamma_v^{pp'}, \quad k = 1, \dots, n_{vF}, v \in V_F, p \in P_v, p' \in P_v, p \neq p', t \in T. \quad (18)$$

Vehicle capacity constraints (between satellites and customers)

$$\sum_{c \in C_s} q_{kvs(c)}^{prt} \leq u_v y_{kvs}^{prt}, \quad k = 1, \dots, n_{vS}, v \in V_S, s \in S, p \in P, r = 1, \dots, m_{vS}, t \in T. \quad (19)$$

$$\sum_{p \in P} \sum_{c \in C_s} q_{kvs(c)}^{prt} \leq u_v, \quad k = 1, \dots, n_{vS}, v \in V_S, s \in S, r = 1, \dots, m_{vS}, t \in T. \quad (20)$$

Compatibility between vehicle types and product types (between satellites and customers)

$$q_{kvs(c)}^{prt} \leq b_v^p u_v, \quad k = 1, \dots, n_{vS}, v \in V_S, c \in C_s, s \in S, p \in P, r = 1, \dots, m_{vS}, t \in T. \quad (21)$$

Vehicle capacity constraints (between L and satellites)

$$\sum_{s \in S} \tilde{q}_{kvs}^{pt} \leq u_v \tilde{y}_{kv}^{pt}, \quad k = 1, \dots, n_{vL}, v \in V_L, p \in P, t \in T. \quad (22)$$

$$\sum_{p \in P} \sum_{s \in S} \tilde{q}_{kvs}^{pt} \leq u_v, \quad k = 1, \dots, n_{vL}, v \in V_L, t \in T. \quad (23)$$

Compatibility between vehicle types and product types (between L and satellites)

$$\tilde{q}_{kvs}^{pt} \leq b_v^p u_v, \quad k = 1, \dots, n_{vL}, v \in V_L, s \in S, p \in P, t \in T. \quad (24)$$

Vehicle capacity constraints (between F and L)

$$\hat{q}_{kv}^{pt} \leq u_v \hat{y}_{kv}^{pt}, \quad k = 1, \dots, n_{vF}, v \in V_F, p \in P, t \in T. \quad (25)$$

$$\sum_{p \in P} \hat{q}_{kv}^{pt} \leq u_v, \quad k = 1, \dots, n_{vF}, v \in V_F, t \in T. \quad (26)$$

Compatibility between vehicle types and product types (between F and L)

$$\hat{q}_{kv}^{pt} \leq b_v^p u_v, \quad k = 1, \dots, n_{vF}, v \in V_F, p \in P, t \in T. \quad (27)$$

Maximum route length constraints – to handle re-fueling, if needed (between satellites and customers)

$$\sum_{i \in C_s^+} \sum_{\substack{j \in C_s^+ \\ i \neq j}} \tau_{ijv} x_{ijkvs}^{rt} \leq \tau_v^{max}, \quad (28)$$

$$k = 1, \dots, n_{vs}, v \in V_s, s \in S, r = 1, \dots, m_{vs}, t \in T.$$

The duration of all routes of one vehicle has to be smaller than the time period duration (for the vehicles traveling between satellites and customers)

$$\sum_{r=1}^{m_{vs}} \left(\sum_{i \in C_s^+} \sum_{\substack{j \in C_s \\ i \neq j}} (\tau_{ijv} + \sigma_{jv}) x_{ijkvs}^{rt} + \sum_{j \in C_s} \tau_{jsv} x_{jskvs}^{rt} + \sum_{c \in C_s} \sum_{p \in P_v} \rho_{vs}^p q_{kvcs(c)}^{prt} \right) \leq \eta^{max}, \quad (29)$$

$$k = 1, \dots, n_{vs}, v \in V_s, s \in S, t \in T.$$

Maximum route length constraints – to handle re-fueling, if needed (between L and satellites)

$$\sum_{i \in S^+} \sum_{\substack{j \in S^+ \\ i \neq j}} \tau_{ijv} \tilde{x}_{ijkv}^t \leq \tau_v^{max}, \quad k = 1, \dots, n_{vL}, v \in V_L, t \in T. \quad (30)$$

The route of each vehicle has to finish within the time period (between L and customers)

$$\sum_{i \in S^+} \sum_{j \in S} (\tau_{ijv} + \sigma_{jv}) \tilde{x}_{ijkv}^t + \sum_{j \in S} \tau_{jLv} \tilde{x}_{jLkv}^t + \sum_{s \in S} \sum_{p \in P_v} \rho_{vL}^p \tilde{q}_{kvps}^{pt} \leq \eta^{max}, \quad (31)$$

$$k = 1, \dots, n_{vs}, v \in V_s, t \in T.$$

Vehicle flow constraints (between satellites and customers)

$$\sum_{j \in C_s^+} x_{cjkvs(c)}^{rt} = \sum_{j \in C_s^+} x_{jckvs(c)}^{rt}, \quad (32)$$

$$c \in C_s^+, s \in S, k = 1, \dots, n_{vs(c)}, v \in V_{s(c)}, r = 1, \dots, m_{vs(c)}, t \in T.$$

$$\sum_{j \in C_s^+} x_{cjkvs(c)}^{rt} \leq 1, \quad (33)$$

$$c \in C_s^+, s \in S, k = 1, \dots, n_{vs(c)}, v \in V_{s(c)}, r = 1, \dots, m_{vs(c)}, t \in T.$$

$$y_{kvs}^{prt} \leq \sum_{j \in C_s} x_{sjkvs(c)}^{rt}, \quad s \in S, k = 1, \dots, n_{vs(c)}, v \in V_{s(c)}, r = 1, \dots, m_{vs(c)}, t \in T, p \in P. \quad (34)$$

Vehicle flow constraints (between L and satellites)

$$\sum_{j \in S^+} \tilde{x}_{sjkv}^t = \sum_{j \in S^+} \tilde{x}_{jskv}^t, \quad s \in S^+, k = 1, \dots, n_{vL}, v \in V_L, t \in T. \quad (35)$$

$$\sum_{j \in S^+} \tilde{x}_{sjkv}^t \leq 1, \quad s \in S^+, k = 1, \dots, n_{vL}, v \in V_L, t \in T. \quad (36)$$

$$\tilde{y}_{kv}^{pt} \leq \sum_{s \in S} \tilde{x}_{Lskv}^t, \quad k = 1, \dots, n_{vL}, v \in V_L, t \in T, p \in P. \quad (37)$$

Vehicle flow constraints (between F and L)

$$\sum_{t'=t}^{t+\delta_v+\varepsilon_v} \hat{x}_{kv}^{t'} \leq 1, \quad k = 1, \dots, n_{vF}, v \in V_F, t \in T \setminus \{t | t + \delta_v + \varepsilon_v > \bar{t}\}. \quad (38)$$

$$\hat{y}_{kv}^{pt} \leq \hat{x}_{kv}^t, \quad k = 1, \dots, n_{vF}, v \in V_F, p \in P, t \in T. \quad (39)$$

Constraints linking variables q and x (between satellites and customers)

$$\sum_{p \in P} q_{kvc s(c)}^{prt} \leq u_v \sum_{j \in C_s^+} x_{jckvs(c)}^{rt}, \quad (40)$$

$$c \in C_s, s \in S, k = 1, \dots, n_{vs(c)}, v \in V_{s(c)}, r = 1, \dots, m_{vs(c)}, t \in T.$$

$$\sum_{p \in P} q_{kvc s(c)}^{prt} \leq u_v \sum_{j \in C_s^+} x_{cjkvs(c)}^{rt}, \quad (41)$$

$$c \in C_s, s \in S, k = 1, \dots, n_{vs(c)}, v \in V_{s(c)}, r = 1, \dots, m_{vs(c)}, t \in T.$$

$$c \in C_s, s \in S, k = 1, \dots, n_{vs(c)}, v \in V_{s(c)}, r = 1, \dots, m_{vs(c)}, t \in T.$$

Constraints linking variables q and x (between L and satellites)

$$\sum_{p \in P} \tilde{q}_{kvs}^{pt} \leq u_v \sum_{j \in S^+} \tilde{x}_{jskv}^t, \quad s \in S, k = 1, \dots, n_{vL}, v \in V_L, t \in T. \quad (42)$$

$$\sum_{p \in P} \tilde{q}_{kvs}^{pt} \leq u_v \sum_{j \in S^+} \tilde{x}_{sjkv}^t, \quad s \in S, k = 1, \dots, n_{vL}, v \in V_L, t \in T. \quad (43)$$

Constraints linking variables q and x (between F and L)

$$\sum_{p \in P} \hat{q}_{kv}^{pt} \leq u_v \hat{x}_{kv}^t, \quad k = 1, \dots, n_{vF}, v \in V_F, t \in T. \quad (44)$$

Subtour elimination constraints (between satellites and customers with $M = |C_{s(c)}^+|$)

$$w_{kvcs(c)}^{rt} \geq w_{kvc's(c')}^{rt} + (M + 1)x_{c'ckvs(c)}^{rt} - M, \quad (45)$$

$$k = 1, \dots, n_{vs(c)}, v \in V_{s(c)}, c \in C_s, c' \in C_s, c \neq c', r = 1, \dots, m_{vs(c)}, s \in S, t \in T.$$

$$w_{kvcs(c)}^{rt} \geq (M + 1)x_{s(c)ckvs(c)}^{rt} - M, \quad (46)$$

$$k = 1, \dots, n_{vs(c)}, v \in V_{s(c)}, c \in C_s, r = 1, \dots, m_{vs(c)}, s \in S, t \in T.$$

$$w_{kvcs(c)}^{rt} \leq |C_{s(c)}|, \quad k = 1, \dots, n_{vs(c)}, v \in V_{s(c)}, c \in C_s, r = 1, \dots, m_{vs(c)}, s \in S, t \in T. \quad (47)$$

$$\sum_{j \in C_s^+} x_{jckvs(c)}^{rt} \leq w_{kvcs(c)}^{rt}, \quad c \in C_s, s \in S, k = 1, \dots, n_{vs(c)}, v \in V_{s(c)}, r = 1, \dots, m_{vs(c)}, t \in T. \quad (48)$$

Subtour elimination constraints (between L and satellites with $M' = |S^+|$)

$$\tilde{w}_{kvs}^t \geq \tilde{w}_{kvs'}^t + (M' + 1)\tilde{x}_{s'skv}^t - M', \quad k = 1, \dots, n_{vL}, v \in V_L, s \in S, s' \in S, s \neq s', t \in T. \quad (49)$$

$$\tilde{w}_{kvs}^t \geq (M' + 1)\tilde{x}_{Lskv}^t - M', \quad k = 1, \dots, n_{vL}, v \in V_L, s \in S, t \in T. \quad (50)$$

$$\tilde{w}_{kvs}^t \leq |S|, \quad k = 1, \dots, n_{vL}, v \in V_L, s \in S, t \in T. \quad (51)$$

$$\sum_{j \in S^+} \tilde{x}_{jskv}^t \leq \tilde{w}_{kvs}^t, \quad s \in S, k = 1, \dots, n_{vL}, v \in V_L, t \in T. \quad (52)$$

Self-loop elimination constraint

$$x_{cckvs(c)}^{rt} = 0, \quad c \in C_s^+, s \in S, k = 1, \dots, n_{vs(c)}, v \in V_{s(c)}, r = 1, \dots, m_{vs(c)}, t \in T. \quad (53)$$

$$\tilde{x}_{sskv}^t = 0, \quad s \in S^+, k = 1, \dots, n_{vL}, v \in V_L, t \in T. \quad (54)$$

To strengthen the routing part, the following inequalities could be added to the formulation similar to those in [Adulyasak et al, 2013] [Archetti et al, 2007, 2011]:

$$x_{ijkvs}^{rt} \leq \sum_{p \in P_v} y_{kvs}^{prt}, \quad i, j \in C_s^+; k = 1, \dots, n_{vs}; v \in V_s; s \in S; r = 1, \dots, m_{vs}; t \in T \quad (55)$$

$$\tilde{x}_{ijkv}^t \leq \sum_{p \in P_v} \tilde{y}_{kv}^{pt}, \quad i, j \in S^+; k = 1, \dots, n_{vL}; v \in V_L; t \in T \quad (56)$$

$$\hat{x}_{kv}^t \leq \sum_{p \in P_v} \hat{y}_{kv}^{pt}, \quad k = 1, \dots, n_{vF}; v \in V_F; t \in T \quad (57)$$

When a vehicle does not transport any product, constraints (55) - (57) force the corresponding x variables to 0. Constraints (55) apply to the routes between a satellite and its customers; constraints (56) to the routes between the close supply node L and the satellites; and constraints (57) to the routes between the far close supply node F and the close supply node L .

Regarding the multi-vehicle aspect, constraints (58) - (60) are valid vehicle symmetry breaking constraints similar to the constraints proposed in [Adulyasak et al, 2013; Adulyasak et al, 2012a] that are shown to significantly improve the performance of the branch-and-bound process. Similarly, we added constraints (61) for the multi-route aspect of the satellite-customer echelon.

$$\sum_{j \in C_s} x_{sjkvs}^{rt} \geq \sum_{j \in C_s} x_{sj(k+1)vs}^{rt}, \quad s \in S; k = 1, \dots, n_{vs} - 1; v \in V_s; r = 1, \dots, m_{vs}; t \in T \quad (58)$$

$$\sum_{j \in S} \tilde{x}_{Ljkv}^t \geq \sum_{j \in S} \tilde{x}_{Lj(k+1)v}^t, \quad k = 1, \dots, n_{vL} - 1; v \in V_L; t \in T \quad (59)$$

$$\hat{x}_{kv}^t \geq \hat{x}_{(k+1)v}^t, \quad k = 1, \dots, n_{vF} - 1; v \in V_s; t \in T \quad (60)$$

$$\sum_{j \in C_s} x_{sjkvs}^{rt} \geq \sum_{j \in C_s} x_{sjkvs}^{(r+1)t}, \quad s \in S; k = 1, \dots, n_{vs}; v \in V_s; r = 1, \dots, m_{vs} - 1; t \in T \quad (61)$$

Constraints (58) - (60) state that the k^{th} vehicle is used before the $(k+1)^{st}$ vehicle, for all three echelons: satellites - customers, close supply node - satellites, far supply node - close supply node, respectively. Constraints (61) state that the r^{th} route of vehicle k is used before the $(r+1)^{st}$ route, between satellite node and its customers.

Additional constraints linking q and y variables (μ is a small number, $0 < \mu < 1$)

$$\sum_{c \in C_s} q_{kvcs}^{prt} + 1 - \mu \geq y_{kvs(c)}^{prt}, \quad k = 1, \dots, n_{vs}, v \in V_s, s \in S, p \in P, r = 1, \dots, m_{vs}, t \in T. \quad (62)$$

Additional constraints linking q and y variables (μ is a small number $0 < \mu < 1$)

$$\sum_{s \in S} \tilde{q}_{kvs}^{pt} + 1 - \mu \geq \tilde{y}_{kv}^{pt}, \quad k = 1, \dots, n_{vL}, v \in V_L, p \in P, t \in T. \quad (63)$$

Additional constraints linking q and y variables (μ is a small number $0 < \mu < 1$)

$$\hat{q}_{kv}^{pt} + 1 - \mu \geq \hat{y}_{kv}^{pt}, \quad k = 1, \dots, n_{vF}, v \in V_F, p \in P, t \in T. \quad (64)$$

Additional constraints linking variables q and x (between L and satellites)

$$\sum_{p \in P} q_{kvcs(c)}^{prt} + 1 - \mu \geq \sum_{j \in C_s^+} x_{jckvs(c)}^{rt}, \quad (65)$$

$$c \in C_s, s \in S, k = 1, \dots, n_{vs(c)}, v \in V_{s(c)}, r = 1, \dots, m_{vs(c)}, t \in T.$$

$$\sum_{p \in P} q_{kvcs(c)}^{prt} + 1 - \mu \geq \sum_{j \in C_s^+} x_{cjkvs(c)}^{rt} \quad (66)$$

$$c \in C_s, s \in S, k = 1, \dots, n_{vs(c)}, v \in V_{s(c)}, r = 1, \dots, m_{vs(c)}, t \in T.$$

Additional constraints linking variables q and x (between L and satellites)

$$\sum_{p \in P} \tilde{q}_{kvs}^{pt} + 1 - \mu \geq \sum_{j \in S^+} \tilde{x}_{jskv}^t, \quad s \in S, k = 1, \dots, n_{vL}, v \in V_L, t \in T. \quad (67)$$

$$\sum_{p \in P} \tilde{q}_{kvs}^{pt} + 1 - \mu \geq \sum_{j \in S^+} \tilde{x}_{sjkv}^t, \quad s \in S, k = 1, \dots, n_{vL}, v \in V_L, t \in T. \quad (68)$$

Additional constraints linking variables q and x (between F and L)

$$\sum_{p \in P} \hat{q}_{kv}^{pt} + 1 - \mu \geq \hat{x}_{kv}^t, \quad k = 1, \dots, n_{vF}, v \in V_F, t \in T \quad (69)$$

Each vehicle route in Echelon 1 (between the close supply node and the satellites) and Echelon 2 (between the satellites and the customer) has to finish in the time period within which it started. This is assured by the constraints (29) and (31). Only the routes in Echelon 0 can spread over several time periods.

The travel times along the edges of the transportation network are dealt with in constraints (28), (29), (30) and (31).

Note that the constraints (7), (8), (9) forbid supplies received during a given time period to be used to satisfy the demand at the same time period. This increases the inventories, but it makes sure that the supply is there when it is needed. On the other hand, this also forbids the supply that arrived in this time period to leave immediately.

These constraints can also be removed, but the danger is that the node may rely on a supply that has not arrived yet (if the demand is at the beginning of the time period and the supplies arrive closer to the end of the time period). This may be overcome by decreasing the duration of the time period. Unfortunately, this might make the constraints (29) and (31) on the route duration infeasible. Another way to resolve these problems is to include time windows on the demand, but this would substantially increase the problem size and the complexity.

Another possibility is to keep the reserve inventories at each store at the level needed to satisfy the demand for one time period. In this case the constraints (7), (8), (9) could be removed and supplies that arrive at a node can immediately be re-loaded and go further.

5.2 Stochastic Model

Now, we consider that the demands are stochastic, and provide some of the possible stochastic models.

The stochastic demand is captured by designing a number of representative demand realization scenarios. This type of approach to solving the stochastic problem is also called *sampling* [Pillac et al, 2013], and it has been proposed as a way of handling the complexities of uncertain environments.

Using sampling, a stochastic model can be designed by generating an Extensive or Explicit Stochastic Form of the problem model – from the deterministic model – in the following manner:

- Add an additional index θ representing a scenario to all scenario-dependent variables and parameters
- Extend the objective function by one more summation multiplying the terms with the probabilities of each scenario.

In order to create this explicit stochastic form, one needs to decide which variables are scenario-dependent. These scenario-dependent variables are called the second-stage variables because their exact values could be decided at the second-stage of the decision-making process when more information about the situation is known. The remaining variables are called the first-stage variables, and they will be assumed not to be scenario-dependent. Their values will determine the plan that will not be changed based on the scenario realization in the real world.

We propose three reasonable decisions for choosing subsets of the scenario-dependent and the scenario-independent variables, *i.e.*, three Explicit Stochastic Models.

Explicit Stochastic Model – *ESM1*:

- the first-stage variables: all routing variables, and
- the second-stage variables: all inventory and flow variables.

Explicit Stochastic Model – *ESM2*:

- the first-stage variables: the routing variables determining the plan for the routing between the far supply node and the close supply node, and
- the second-stage variables: all other variables.

Explicit Stochastic Model – *ESM3*:

- the first-stage variables: all the routing variables, and the flow variables determining the quantities moved between the far supply node and the close supply node, and
- the second-stage variables: all other variables.

The mathematical programming formulation will be as follows: all second-stage variables will get an additional index θ and the objective function will change to account for the different scenarios and their probabilities b_θ .

6 Computational Study

This section describes a small preliminary computational study.

The proposed deterministic model is solved using Gurobi. The solutions to three deterministic problem instances are provided together with the outcome of solving one stochastic problem instance with three scenarios.

Computational experiments were conducted on a system with the following basic specifications:

- RedHat Linux x64 version 4.4.7.3
- 4x Intel(R) Xeon(R) CPU E5-1607 0 @ 3.00GHz
- 32GB RAM
- Java Development Kit version 1.7.0_25
- Gurobi version 5.5.0

The solver code is developed in Java using the Gurobi Java API¹. Java and Gurobi are configured following standard installation guides provided. No specific configuration changes were made to either one in order to support this computational study. Gurobi is able to leverage the multi-core capabilities of the system internally. No configuration on the part of the developer or user is required. Gurobi prints information to the console noting how many cores it is using.

This initial computational study is performed to validate the model and the software implementation and to provide indication of the running times for different problem sizes. The solutions to the deterministic problem with different levels of the demand are provided in Table 6-1: the best solutions for high, medium and low demand for one product - water. The demands are assumed to be 10, 6, and 2 litres of water per day per person correspondingly. The number of transportation assets is 3, 30, and 10, at each node at the three echelons correspondingly.

A time limit of 5 minutes is given to Gurobi.

¹ Together with Darren Thomson, Mohsen Ghazel helped with the implementation.

Table 6-1 Deterministic Problem Instances

Problem instance	CPU time	Optimality Gap	Best solution value	Transportation cost (weight, cost)	Distances travelled per each echelon and total	Transp. costs per each echelon and total	Inventory costs (weight, cost)	Inventory amounts per each echelon	Inventory costs per each echelon	Unmet demand
Medium demand	5 min	1.87%	3,973,590.11	0.2 717,974.09	1,800.00 7,392.73 10,404.68 19,597.41	2,700,000.00 369,636.48 520,233.95 3,589,870.43	0.2 15,616.02	1,462.00 1,581.99 2,382.01 5,426.00	14,620.00 15,819.90 47,640.20 78,080.10	20.0% (Initial periods only)
High demand	5 min	2.47%	6,662,191.07	0.2 1,137,949.51	3,000.00 10,989.19 12,805.76 26,794.95	4,500,000.00 549,459.63 640,287.94 5,689,747.57	0.2 23,341.56	2,589.83 2,520.17 3,280.39 8,390.39	25,898.30 25,201.70 65,607.80 116,707.80	20.4% (Initial periods only)
Low demand	5 min	2.51%	1,333,542.42	0.2 243,994.42	600.00 2,397.64 4,001.80 6,999.44	900,000.00 119,882.10 200,089.98 1,219,972.08	0.2 9,548.00	558.00 624.00 1,796.00 2,978.00	5,580.00 6,240.00 35,920.00 47,740.00	20.0% (Initial periods only)

The number of variables (total, binary, integer) for the problems in the table are 238,335; 187,740; and 214,740, respectively. The number of constraints is 673,305.

The unmet demand rates of 20% are the result of the initial condition where all inventory is located at the far supply node, with no inventory anywhere else. As a result, demand in the first three periods can never be met. When looking at 15 time periods, this means 20% is the minimum value for unmet demand.

The transportation cost is the product of the distance traveled, the asset fuel consumption rate, and the cost of gasoline. The weighted cost is, *e.g.*, the transportation cost multiplied by the weight, *e.g.*, 0.2.

The problem instances are characterized by the following: the SCN has 3 satellite nodes, 6 demand nodes per satellite (18 demand nodes in total), and 1,000 people per demand node. The number of time periods is 15 and the time period is one week. Thus, the time horizon is 15 weeks. There is single product. The weights of the objective function are: (0.2, 0.2, 0.2, 0.2, 10,000).

An SCM simulator, developed using a Discrete Event Simulation (DES) open source tool SimPy, has been used to execute solutions generated by the SCM problem solver and record the changes in the inventory levels. The SCM simulator uses the supply chain structure together with the delivery amounts and routes generated by the solver. To validate the outputs of our computational study, the solutions generated from the average and maximum demand cases were used. In both cases, the consumption levels are set to be at the maximum demand level.

The inventories observed at a demand node are shown in Figure 6-1. At the demand node, there are shortages resulting in unmet demand through time periods 0, 1, 3, 7, 8, 9, 12, and 13 when using the average demand solution. On the other hand, there are only shortages during periods 0, 1, and 2 when using the maximum demand solution, and these are purely the result of the initial inventory being 0 throughout the supply chain, meaning that it takes at least 2 full time periods before any inventory can possibly arrive at the demand nodes.

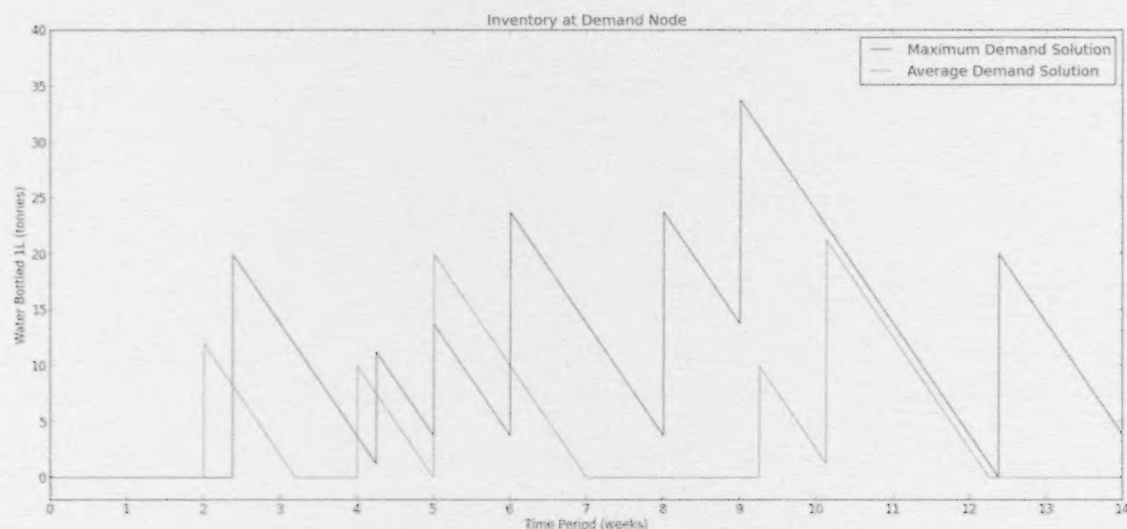


Figure 6-1 Inventory at Demand Node

The impacts of the demand can be seen throughout the supply chain, as both the satellite and close supply nodes maintain higher inventories (and thus higher costs) through the time period studied.

Also, at this stage, the demands are equal for each time period. The recommendation is that more comprehensive computational study needs to be done, but extensive consultation between subject matter experts and decision makers is needed to set all the parameters and generate appropriate problem instances thus also limiting the variations to a reasonable number, so that the study is feasible and extensive enough.

We have been able to implement the explicit form of the stochastic model (ESM1), and we succeeded running the problem instance similar to those we reported on in the table. The stochastic problem has 3 scenarios. The probabilities of the scenarios are 0.33. The number of variables was 805,545; 619,740; 668,340 for total, binary, and integer, respectively. The number of constraints was 2,162,265. The stochastic problem was run for 100 minutes and generated a feasible solution with an optimality gap of 0.057%.

7 Conclusions

We developed a model and a solver for the three-echelon supply chain management problem. We started from the deterministic version of the problem since it is needed before the stochastic version of the problem can be tackled. The accomplishments of this initial project include:

- Performed a literature survey of humanitarian disaster relief operations and two-echelon SCM problem models, including the following characteristics: multi-products, heterogeneous fleets, inventory capacities, uncertainty, and risks.
- Created a mathematical programming formulation of the deterministic version of the Supply Chain Management (SCM) problem – integrating the distribution (transportation) and inventory management problems. Characteristics include: three-echelon, multi-products, multi-periods, heterogeneous fleets, heterogeneous stores, inventory capacities.
- Modeled the uncertainty to demand using scenarios
- Implemented the mathematical programming formulation in Gurobi API and a solver for the problem
- Created an SCM discrete-event simulator for testing the solutions generated by the solver
- Created a problem instance generator
- Performed an initial computational study
- Refined the IP model

The novelties of the proposed models compared to the published research include:

- Integration of inventory management in a multi-echelon vehicle routing problem
- Multiple realistic problem characteristics – multiple products, heterogeneous fleet, multiple periods, compatibility constraints – that have been considered separately in various multi-echelon VRP or SCM models, but never all at once in the same problem.
- Stochastic demand with combination of all characteristics and features listed in the previous bullet.

- Extension of the two-echelon network with an additional level – made of a unidirectional link between a far supply node and a close supply node – that must be handled in a particular way, when compared to the rest of the network, due to a different time scale.
- Multi-echelon routing problems often involve different types of vehicles, but fleets are homogeneous by level; our problem is different because it considers heterogeneous fleets at each level.

References

- [Anily and Federgruen, 1993] A. Anily and A. Federgruen, "Two-echelon distributions systems with vehicle routing costs and central inventories", *Operations Research* 41, 37-47, 1993.
- [Archetti et al, 2007] Archetti, C., L. Bertazzi, G. Laporte, and M. G. Speranza, "A branch-and-cut algorithm for a vendor-managed inventory-routing problem", *Transportation Science* 41, 382-391, 2007.
- [Archetti et al, 2011] Archetti, C., L. Bertazzi, G. Paletta, and M. G. Speranza, "Analysis of the maximum level policy in a production-distribution system", *Computers and Operations Research* 38, 1731-1746, 2011.
- [Berger et al, 2012] J. Berger, A. Boukhtouta, S. Mitrovic-Minic, and J. Conrad, "Decision support capability for in-theatre logistics planning and sustain missions – problem definition", DRDC – Valcartier Technical Report, October 2012.
- [Cdn ADO] The Canadian Army booklet on Adaptive Dispersed Operations (ADO).
- [Conrad, 2009] Lieutenant Colonel John Conrad, "What the Thunder, Reflections of a Canadian Officer in Kandahar," The Dundurn Press, 2009.
- [Caramia and Dell'Olmo, 2008] M. Caramia and P. Dell'Olmo, "Multi-objective Management in Freight Logistics: Increasing Capacity, Service Level and Safety with Optimization Algorithms", Springer, 2008.
- [Chandraprakaikul, 2010] W. Chandraprakaikul, "Humanitarian supply chain management: Literature review and future research", Working paper, University of the Thai Chamber of Commerce, Bangkok, Thailand, 2010.
- [Crainic et al, 2008] T.G. Crainic, S. Mancini, G. Perboli, and R. Tadei, "Clustering-based heuristics for the two-echelon vehicle routing problem", Technical Report, CIRRELT-2008-46, 2008.
- [Crainic et al, 2008] T.G. Crainic T.G., S. Mancini, G. Perboli, and R. Tadei, "Lower bounds for the two-echelon vehicle routing problem", EU/Meeting, Troyes, France, 2008.
- [Crainic et al, 2009] T.G. Crainic, N. Ricciardi, and G. Storchi, "Models for evaluating and planning city logistics systems", *Transportation Science* 43, 432-454, 2009.

- [Crainic et al, 2010] T.G. Crainic, S. Mancini, G. Perboli, and R. Tadei, "Two-echelon vehicle routing problem: A satellite location analysis", *Procedia – Social and Behavioral Sciences* 2, 5944-5955, 2010.
- [Crainic et al, 2011a] T.G. Crainic, S. Mancini, G. Perboli, and R. Tadei, "Multi-start heuristics for the two-echelon vehicle routing problem", In: *EvoCOP 2011*, P. Merz and J.-K. Hao (Eds.), *Lecture Notes in Computer Science* 6622, 179-190, 2011.
- [Crainic et al, 2011b] T.G. Crainic, X. Fu, M. Gendreau, W. Rei, and S.W. Wallace, "Progressive hedging-based meta-heuristics for stochastic network design", *Networks* 58, 114-124, 2011.
- [Crainic et al, 2012] T.G. Crainic, S. Mancini, G. Perboli, and R. Tadei, "GRASP with path relinking for the two-echelon vehicle routing problem", *Technical Report, CIRRELT-2012-45*, 2012.
- [Dondo et al, 2009] R. Dondo, C.A. Méndez, and J. Cerdá, "Managing distribution in supply chain networks", *Industrial & Engineering Chemistry Research* 48, 9961-9978, 2009.
- [Dondo et al, 2011] R. Dondo, C.A. Méndez, and J. Cerdá, "The multi-echelon vehicle routing problem with cross docking in supply chain management", *Computers and Chemical Engineering* 35, 3002-3024, 2011.
- [Doyen et al, 2012] A. Döyen, N. Aras, and G. Barbarosoglu, "A two-echelon stochastic facility location model for humanitarian relief logistics", *Optimization Letters* 6, 1123-1145, 2012.
- [Gonzalez-Feliu et al, 2006] Gonzalez-Feliu, J., Perboli G., Tadei R., Vigo D., "The two-echelon capacitated vehicle routing problem", *Technical Report OR/04/06*, Politecnico di Torino, Italy, 2006.
- [Haugen et al, 2001] K.K. Haugen, A. Lokketangen, and D. Woodruff (2001) "Progressive hedging as a meta-heuristic applied to stochastic lot-sizing", *European Journal of Operational Research*, 132, 116-122.
- [Hemmelmayr et al, 2012] V.C. Hemmelmayr, J.-F. Cordeau, and T.G. Crainic, "An adaptive large neighborhood search heuristic for two-echelon vehicle routing problems arising in city logistics", *Computers & Operations Research* 39, 3215-3228, 2012.
- [Jacobsen and Madsen, 1980] S. Jacobsen and O. Madsen, "A comparative study of heuristics for a two-level routing-location problem", *European Journal of Operational Research* 5, 378-387, 1980.
- [Jepsen et al, 2013] M. Jepsen, S. Spoorendonk, and S. Ropke, "A branch-and-cut algorithm for the symmetric two-echelon capacitated vehicle routing problem", *forthcoming in Transportation Science*.
- [Jung and Mathur, 2007] J. Jung and K. Mathur, "An efficient heuristic algorithm for a two-echelon joint inventory and routing problem", *Transportation Science* 41, 55-73, 2007.
- [Jung, 2012] J. Jung "An effective genetic algorithm for solving the joint inventory and routing problem with multi-warehouses", *Korean Management Science Review* 29 (3), 107-120, 2012.

- [Kovacs and Spens, 2007] G. Kovács G. and K.M. Spens, "Humanitarian logistics in disaster relief operations", *International Journal of Physical Distribution & Logistics Management* 37, 99-114, 2007.
- [Mancini, 2012] S. Mancini, "The two-echelon vehicle routing problem", *4OR – A Quarterly Journal of Operations Research* 10, 391-392, 2012.
- [Martinez et al, 2011] A.J. Pedraza Martinez, O. Stapleton, and L.N. Van Wassenhove, "Field vehicle fleet management in humanitarian operations: A case-based approach", *Journal of Operations Management* 29, 404-421, 2011.
- [Max Shen, 2007] Z.-J. Max Shen, "Integrated supply chain design models: A survey and future research directions", *Journal of Industrial and Management Optimization* 3, 1-27, 2007.
- [MC_2011] Snezana Mitrovic Minic and John Conrad (2011) "Issues and Challenges Related to the Tactical and Operational Logistics" Final Report, DRDC, MDA Report RX-RP-53-1747, February 9, 2011.
- [Mumtaz and Brah, 2010] M. Kamran Mumtaz and S.A. Brah, "Integrated location and inventory decision problem in a three-tier supply chain network" 16 pages, 2010.
- [Najafi et al, 2013] Mehdi Najafi, Kourosh Eshghi, and Wout Dullaert "A multi-objective robust optimization model for logistics planning in the earthquake response phase", *Transportation Research Part E* 49 (2013) 217-249.
- [Ngueveu et al, 2010] Sandra Ulrich Ngueveu, Christian Prins, and Roberto Wolfler Calvo (2010) "A Hybrid Tabu Search for the m -Peripatetic Vehicle Routing Problem", *Mathheuristics, Annals of Information Systems* 10, 2010, pp 253-266.
- [Nikbakhsh et al, 2011] E. Nikbakhsh and R. Zanjirani Farahani, "Humanitarian logistics planning in disaster relief operations", In: *Logistics Operations and Management: Concepts and Models*, R. Zanjirani Farahani, S. Rezapour, L. Kardar (Eds.), pp. 291-332, Elsevier, London, UK, 2011.
- [Perboli and Tadei, 2010] G. Perboli and R. Tadei, "New families of valid inequalities for the two-echelon vehicle routing problem", *Electronic Notes in Discrete Mathematics* 36, 639-646, 2010.
- [Perboli et al, 2011] G. Perboli, R. Tadei, and D. Vigo, "The two-echelon capacitated vehicle routing problem: Models and math-based heuristics", *Transportation Science* 45, 364-380, 2011.
- [Perron et al, 2010] S. Perron, P. Hansen, S. Le Digabel, and N. Mladenovic, "Exact and heuristic solutions of the global supply chain problem with transfer pricing", *EJOR* 202, pp 864-879, 2010.
- [Pillac et al, 2013] V. Pillac, M. Gendreau, C. Gueret, and A.L. Medglia, "A review of dynamic vehicle routing problems", *EJOR* 225, pp 1-11, 2013.
- [Rockafellar and Wets, 1991] R.T. Rockafellar and R.J.-B. Wets, "Scenarios and policy aggregation in optimization under uncertainty", *Mathematics of Operations Research* 16(1), 119-147, 1991.
- [Santos et al, 2013] F.A. Santos, A.S. da Cunha, and G.R. Mateus, "Branch-and-price algorithms for the two-echelon capacitated vehicle routing problem", *Forthcoming in Optimization Letters*.

- [VanWassenhove et al, 2012] L.N. Van Wassenhove and A.J. Pedraza Martinez, "Using OR to adapt supply chain management best practices to humanitarian logistics", *International Transactions in Operational Research* 19, 307-322, 2012.
- [Voudouris et al, 2010] C. Voudouris, E.P.K. Tsang, and A. Alsheddy, "Guided Local Search", in *Handbook of Metaheuristics*, Second Edition, Gendreau M. and Potvin J.-Y. Editors, pp. 321-361, Springer, 2010.
- [YCK_2012] W. Yang, F.T.S. Chan, and V. Kumar (2012) "Optimizing replenishment policies using Genetic Algorithm for single-warehouse multi-retailer system", *Expert Systems with Applications*, Volume 39, Issue 3, 15 February 2012, Pages 3081–3086.